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A whole life cycle performance-based ECOnomic and ECOlogical assessment framework (ECO_2) for concrete sustainability

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Abstract

Concrete is the primary building material worldwide with a substantial impact on the built environment sustainability. Hence, it is necessary to assess concrete's combined functionality, economic and environmental impact. In this paper, two concrete sustainability assessment frameworks, MARS-SC and CONCRE*Top*, were studied. Building on the identified gaps, a new framework, ECO_2 was developed. ECO_2 is a multi-criteria decision analysis framework that accounts for carbon sequestration of concrete, impact allocation of raw materials, and the impact from the use and end-of-life phases. Hence, it could be used to optimize the proportions of a concrete mix based on a user-defined sustainability objective. A case study concluded that, due to the whole life cycle scope, the environmental impact calculated through ECO_2 is 20% higher than that by MARS-SC and CONCRE*Top*. In case of reinforced concrete, where service life requirements are different, the ranking of the alternatives according to ECO_2 will significantly change comparatively.

1. Introduction

The construction industry is one of the most significant contributors to the world economy and hence to its deteriorating ecology. In order to follow the global direction, policy makers are examining several laws and regulations that ensure a more sustainable built environment [1]. The UK government issued the climate change act in 2008, which was the first time a country had introduced a legally binding framework for tackling climate change. The Act sets targets, establishes systems to ensure accountability and addresses resilience to climate change [2]. In 2006, the UK government committed that from 2016 all new homes would be 'zero carbon' and introduced the "Code for Sustainable Homes", against which the sustainability of new homes could be rated. This was translated into the development of the ENVEST tool by the Building Research Establishment Environmental Assessment Method (BREEAM), upon which points are determined for the environmental impact assessment and rating of buildings as a whole [3]. However, the focus of this rating system in the construction industry is on reducing the operational energy consumption by buildings, while not the environmental impact of the building materials. The same goes for PAS 2050, a document that provides guidelines for the environmental impact assessment studies by the British Standards Institution [4]. These assessment methods are fundamental for setting targets for companies and regulatory boards [5]. However, it appears then that there is a gap in the legislation side when it comes to sustainability assessment of building materials.

Concrete is the most consumed building material on Earth [6]. The global yearly rate of production of concrete is almost 2 tonnes per capita [7]. Nevertheless, projections indicate that the need for urbanization would double this figure by 2050 [8]. Concrete's versatility stems from its inherent strength and durability properties [9]. Concrete is also considered an economic solution compared to similarly reliable building materials such as steel and timber [10]. Socially, around 5% of the job market is guaranteed through concrete related industries [11]. However, the use of concrete is associated with negative environmental impacts [12]. The current production rate of more than 4 billion tonnes of ordinary Portland cement (OPC) annually is responsible for 7% of the global CO_2 emissions [13]. It also risks depleting natural resources since more than 50 Billion tonnes of aggregates are being extracted annually [7]. Concrete has a carbon footprint of 300 kg CO_2-eq/m^3 on average of which 90% are attributable to OPC [14].

A recent systematic review concluded that Green concrete alternatives could decrease the embodied carbon of the resulting concrete till 100 kg CO_2-eq /m^3. First, recycling aggregate concrete (RAC) where construction and demolition waste (CDW) as aggregates in concrete. This reduces the landfilling potential by 50-75% of concrete and its embodied carbon by 10-30% [6; 15; 16]. Blended cement concrete (BCC) is where OPC in the binder is partially replaced with various supplementary cementitious materials (SCMs). Examples of these are fly ash (FA), which is a by-product of coal combustion, ground granulated blastfurnace slag (GGBS) which is a by-product of steel manufacturing, silica fume (SF) which is generated from glass manufacturing as well as calcined clay (CC) [17]. Therefore, the embodied emissions of concrete could decrease up to 30% and 60% with incorporation of 35% and 70% of FA and GGBS, respectively [18]. Also, through fully replacing OPC, alkali activated concretes (AAC) are made with precursors of 100% FA, CC or GGBS that are activated using an alkaline solution yielding 70-75% less emissions than OPC concrete.

The environmental enhancements to Green concrete mixes could be, on the downside, associated with deterioration in the functional aspects and an increase in cost of concrete [19]. Sustainability, in general, is a multi-faceted notion that outlines the nature and impact of human activity on the current and future means of life [20]. The classical definition of sustainability dictates a combination of the environmental, economic and social aspects of the subject matter [21]. A typical sustainability assessment model should include one of more of these aspects to judge the sustainability of a certain product [22]. A multi-criteria decision analysis (MCDA) methodology is the main decision support technique used to evaluate alternative(s) based on a set of indicators to judge on the sustainability [23]. Besides the ability to build a judgement on the sustainability of a concrete mix based on several pillars, an MCDA method also allows for the optimization of concrete mixing proportions based on a user-defined objective function.

Across the literature, several frameworks were found that used MCDA methodology for concrete sustainability assessment (SA) based on two or more pillars of sustainability. In 2004, Lippiatt and Ahmed published a SA framework called BEES: Building for Environmental and Economic Sustainability [24]. After that, several researchers developed a Methodology for the Relative SA of Residential Buildings (MARS-H, from the Portuguese acronym), which is another binary MCDA framework that combines economic and environmental indicators [25].

Nevetheless, Rahla et al. (2019) modified the MARS-SC framework to include the performance of concrete as a third pillar to concrete sustainability. It will be referred to as MARS-MOD in this dissertation [26]. Recently, another MCDA framework was developed at the Instituto Superior Técnico in Lisbon combining the environmental, economic and performance indicators of concrete, "CONCRETop" [27]. The final two frameworks are the most comprehensive in the literature, but throughout this paper it will show that there still remains a lot of improvement to make.

2. Methodology

The first objective of this paper is to exhibit the shortcomings in both the MARS-SC and the CONCRE*Top* concrete sustainability frameworks. A MCDA methodology follows a standard process starting with the problem definition, the identification of the parameters used for comparison and the assessment of the studied alternatives using these parameters to help users make a judgment on their sustainability. Hence, this process is followed throughout the next section to help identify the gaps in the methodology of both frameworks. After that, the same process will be used to explain the features of the newly developed framework (ECO_2). As will be explained later, the novel framework provides a paradigm shift to sustainability assessment towards a performance based approach. Finally, a case study is prepared to validate the ECO_2 framework and compare its findings with the two aforementioned ones.

3. Critique of existing frameworks

3.1. *Step 1: Define scope*

3.1.1. Level 1

A MCDA sustainability assessment framework is typically divided into three levels (Figure 1): the sustainability index, the pillars of sustainability, and the indicators used to quantify each pillar [28]. The goal of both MARS-SC and CONCRE*Top* is the same; to assess the sustainability of concrete.

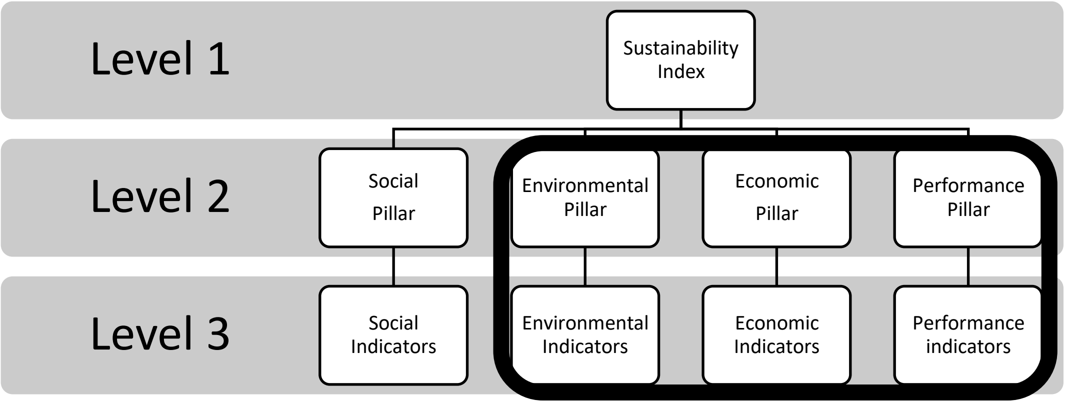

Figure 1: A schematic of the 3 levels of a typical MCDA framework scope omitting the social pillar

3.1.2. Level 2

Contrary to the famous triple bottom line (social, economic and environmental) sustainability assessment scope agreed in the literature; most frameworks ignore the social impact pillar. The social pillar is more popular among frameworks related to construction works in which different methods of construction would influence social indicators such as job creation and/or willingness to pay [23]. However, the scope of both frameworks understudy is the sustainability of concrete as a building material. Therefore, as seen in Figure 2, the social pillar is considered as out of scope.

In exchange, MARS-SC and CONCRE*Top* added the "performance" of concrete alternatives as a third pillar of sustainability as shown in Figure 2. As established in the literature, the extensive use of concrete in infrastructure is mainly due to its ability to fulfil in-service requirements such as constructability, strength and durability [29]. Hence, the performance related parameters usually serve as the principal basis for concrete selection rather than environmental impact or cost [30]. It is therefore necessary to include a measure of performance, which is referred to in the MARS-SC framework in Figure 2 as the functional pillar, in the sustainability assessment of concrete [31].

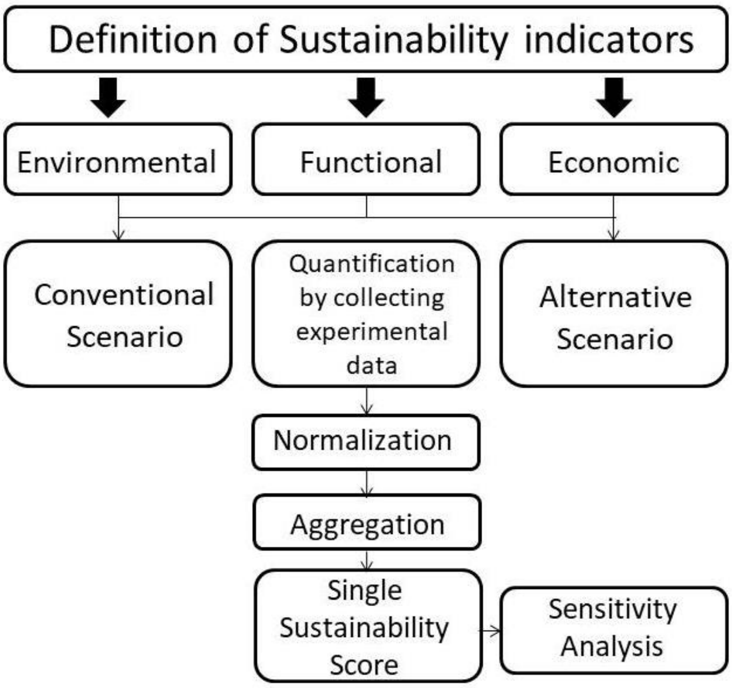

Figure 2: The MARS-SC MCDA framework for concrete sustainability assessment [26]

3.1.3. Level 3

The third level is concerning the selected indicators for the assessment of each of the pillars. According to Menoufi et al. (2011), a sustainability indicator is key to the reliability of a MCDA and it should be suitable for communicating the objectives of the framework to the intended stakeholders [32]. The calculation process of the sustainability index in both frameworks under study is the same. The environmental indicators are summed up into a single environmental indicator, as well as the functional and economic ones. The sustainability index is calculated through adding the score of all three impact categories: functional, environmental and economic. In both frameworks, this is done through a “additive-aggregation” process which considers compensatory rationality. For example, an alternative x could have an overall higher sustainability index than alternative z although it had a lower environmental and economic score. This is due to the former scored a higher functional impact with a large enough margin than the latter that it overtook the difference in the 2 other pillars.

3.2. *Step 2: Define alternatives*

In order to compare between different concrete alternatives, it is required for the user of any of the MCDA frameworks to define them. In both frameworks, MARS-SC and

CONCRE*Top*, an alternative is simply a concrete mix. Defining an alternative is done by specifying the mixing proportions of each of the constituents used in each mix. The first gap identified in the existing frameworks is the absence of scenario analysis. Assuming different scenarios is vital to tackle the uncertainty in LCA of concrete. Possible scenarios include fluctuating market prices, project specifications and the weights assigned to indicators.

3.3. *Step 3: Define LCA system boundary*

The methodology used to study the economic and environmental impact is the life cycle assessment (LCA) and Life cycle costing (LCC). A LCA study is divided into 4 main stages: 1) scope and goal definition, 2) inventory identification for the life cycle processes, 3) characterization and assessment of the life cycle impact and 4) interpretation of results [33]. The first stage, which is the definition of goal and scope, involves the system boundary and the functional unit selection. A system boundary of a concrete product could be Cradle-to-Gate, which means including all processes and emissions until the production of its different constituents or Cradle-to-Grave which includes the “Use” and “End-of-Life” phases or Cradle-to-Cradle including the negative impact from recycling a landfilled material in a new concrete. The second gap found in both frameworks, MARS-SC and CONCRE*Top*, is that the scope specified is only Cradle-to-Gate. However, it is recommended for a reliable LCA study of concrete to either be Cradle-to-Grave or Cradle-to-Cradle [34].

3.4. *Step 4: Calculate LCA Functional Unit*

The functional unit (FU) is a key element in a LCA and is responsible for the quantification of the environmental and economic impact indicators[35]. Hence, its selection needs to be reflective of the nature of the LCA logic [20]. That is why, in the MARS-SC and CONCRE*Top* frameworks, the functional unit is assumed as simply a unit volume of concrete (1 m^3). In both frameworks, functional indicators are quantified through a process similar to the environmental and economic indicators. This is the third gap in this critical analysis of the frameworks because the FU used in the LCA of the MCDA should be indicative of the performance of concrete.

3.5. *Step 5: Collect LCA Inventory Data*

The second stage of a LCA study is the life cycle inventory data collection. This is the data collection stage, in which the input and output factors, such as energy, raw materials, products, and waste, are analysed for the LCA of concrete. The inventory data for a concrete mix mainly include: 1) upstream processes: those involved in the production of each of the constituents and its transportation till the concrete production plant, 2) core processes which involve the energy and emissions required for mixing concrete and transportation to site, and 3) downstream processes needed for the demolition or any other end-of-life scenario [36]. Examining the literature, it was apparent that both frameworks only included inventory data concerning upstream processes. This is consistent with their selected Cradle-to-Gate scope. However, this is not the best practice as it underestimates the environmental impact of the considered alternatives. This is highlighted as the fourth gap in this paper.

The source of concrete inventory data could be: primary data from the building industry to which the user has access, as accredited environmental databases such as Ecoinvent, GaBi and EuGeos or Environmental Product Declarations (EPDs) [37]. EPDs are standardized documents to communicate the environmental performance of a product [38]. Although databases such as EcoInvent and GaBi are updated annually to reflect any changes in the inventory data included, Hafliger et al. (2017) suggest that the priority in the source of upstream processes is for EPDs of the actual constituents in the mix [39]. The fifth recommendation is for concrete sustainability frameworks to prioritize primary data and allow mixing several sources.

The third component of inventory data is impact allocation; the process of portioning the environmental burden of the original process to the waste material being recycled in the product under study [40]. Interpreting the EU directive 2008 conditions, FA, GGBS and SF ought to be considered as by-products and not as waste [41]. This means that they are ought to be allocated a percentage of the environmental burden of their original production process, which are coal combustion, steel production and glass manufacturing respectively [41]. Neither MARS-SC nor CONCRE*Top* considers the impact allocation in the inventory data collection, which is the sixth gap presented in this section.

3.6. *Step 6: Calculate the sustainability index*

The final step of the sustainability assessment process is to calculate the sustainability index. For each alternative, the functional parameters are measured or deduced and the same for the environmental and economic parameters. Using the weights of each, the average value between them is calculated as the sustainability index. Both frameworks followed the same calculation method. However, according to Cinelli et al. (2014), a sustainability framework should have a user-friendly tool in order to allow users to apply it to the objective alternatives [22]. Hence, the final gap found in MARS-SC and CONCRE*Top* is the fact that there were no tools available for users to apply.

3.7. *Summary of gaps in existing frameworks*

The summary of the gaps found in the two frameworks, MARS-SC and CONCRE*Top* reviewed are as follows:

i. Allowing for different scenarios for comparison between alternatives.
ii. The LCA scope should be either Cradle-to-Grave or Cradle-to-Cradle.
iii. Instead of being a separate pillar of sustainability, functional parameters should be integrated in the LCA as the functional unit.
iv. Following on the Cradle-to-Grave scope, the LCA inventory data should include upstream and downstream data.
v. Primary sources such as site specific data should be prioritized as a source of inventory data.
vi. Impact allocation for SCM based concrete should be included.

4. The ECO_2 sustainability framework

4.1. *Background*

Before introducing the features of the new framework that builds on the identified gaps in the existing ones, it is necessary to explain the core of its logic. The ECO_2 is primarily a performance based framework for concrete sustainability assessment. The term performance based is associated with a trend in specifying concrete durability called performance based specifications. For years, concrete durability was determined using prescriptive specifications – sometime referred to as deemed to satisfy specifications- which included constraints such as minimum cement content, maximum SCM use and maximum water to binder (w/b) ratio [43]. Standards such as ACI 308-01 ensure an optimum concrete performance by restricting these ratios to certain ranges. However, this rigid nature of the prescriptive based specifications is not ideal when it comes to sustainability. Due to the wide range of performance requirements in concrete applications, specifications for concrete should be flexible and focusing on the intended project application [44]. The definition of performance based specifications given by the Canadian standard CSA A 23.1is "A specification method in which the final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods.

Both MARS-SC and CONCRE*Top* include the functional properties of concrete as a separate pillar of sustainability. This means that, similar to the durability prescriptive specifications, this sustainability pillar is quantified regardless of the intended application of the concrete alternative. According to Rahla et al. (2019), a project that requires a concrete with a minimum strength of 30 MPa and service life of 50 years is assessed, as per the criteria aforementioned for the MARS-SC framework [26]. Hence, for this project, 3 concrete mixes that exhibit compressive strength of 30, 40 and 60 MPa respectively would be assessed using the MARS-SC framework with a normalized impact of 1/2: 2/3: 1. This means that the extra environmental and economic impact invested in making alternatives 2 and 3 of higher strength would be rewarded, which is not the best practice for sustainability. According to Muller et al. (2016), using concrete with superior functional properties than the project requirement is a waste of resources and should be penalized when assessing the sustainability rather than rewarded [45].

This is the core of the logic behind the ECO_2 framework. As seen in Figure 3, the framework overcomes the third gap from the reviewed frameworks concerning accounting for the performance of concrete alternatives in a prescriptive method. Instead, the ECO_2 framework includes user-defined project specification as the basis for assessing the functional impact. The user defined functional requirements are specific to the intended application of concrete whether the structure is a dam, a skyscraper or a highway. This renders the comparison between the different concrete alternatives credible only within the defined boundary of the project requirements. Hence, for the aforementioned example of the 3 concrete mixes with a compressive strength of 30, 40 and 60 MPa, would be considered as being of equal functional performance since the project only requires a compressive strength of 30 MPa. The functional impact of the studied concrete alternatives is then translated into the functional unit to be used for the LCA study.

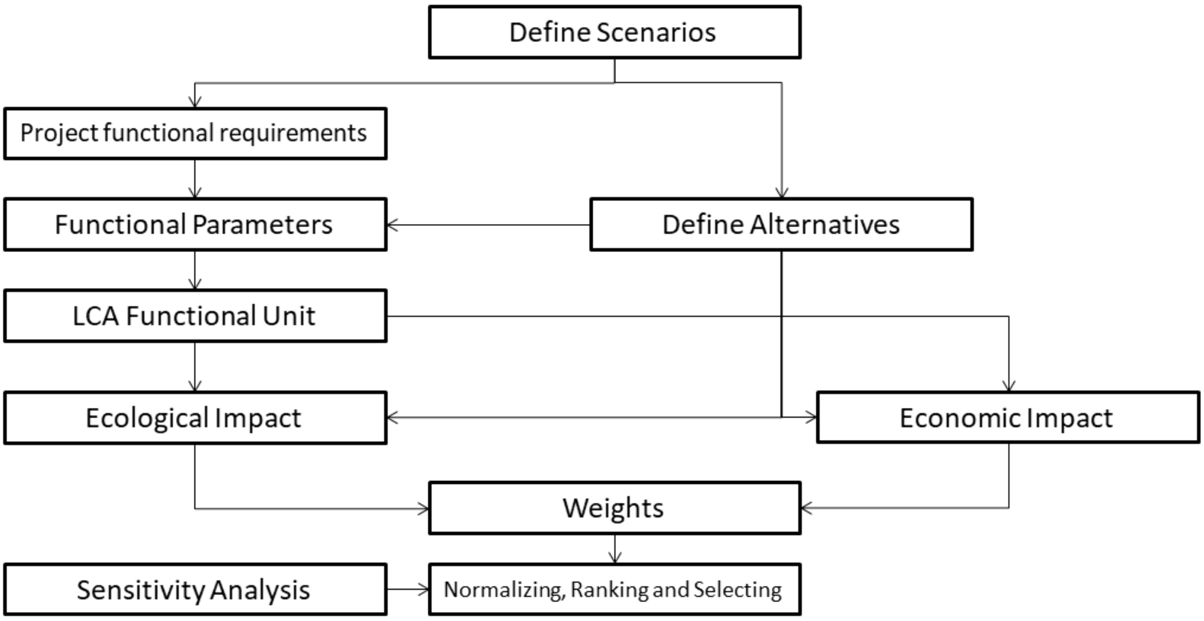

Figure 3: A schematic of the logic followed by the ECO_2 sustainability assessment framework

4.2. *Step 1: Define scope*

Similar to that of both reviewed frameworks, the goal of ECO_2 is to sustainability assessment of concrete. For ECO_2 the users could be anyone with the objective of assessing a set of concrete alternatives against project specifications. The selected sustainability indicators for each of the frameworks understudy as well as that of ECO_2 could be summarized in table 1. As explained in the introduction, the functional indicators in ECO_2 are not included in the aggregated sustainability score. Following the best practice for sustainability assessment, it is translated into the functional unit of the LCA for the environmental and economic impact. Although the indicators used for environmental impact in ECO_2 are less than MARS-MOD, it is established by the literature that these are the most reliable and indicative mid-point indicators [27]. A new indicator, Y – Combined ecological impact, was developed in ECO_2 to measure the ecological impact combining the normalized values of the selected mid-point indicators based on the performance based functional unit. Also, the economic impact according to ECO_2 is calculated using a new indicator, Z - Net present value, that is based on a whole life cycle cost assessment considering the interest rate and inflation rate which is more reliable than the baseline cost of the concrete alternative [46]. Finally, the ECO_2 index is the third indicator that was developed in the framework to combine Y and Z for a given alternative.

***Table 1: A table summarizing the selected indicators of the ECO$_2$ framework compared to MARS-SC and CONCRE*Top**

Sustainability Pillars	Indicators	Previous frameworks		Proposed framework
		MARS-SC	CONCRE*Top*	ECO$_2$
Functional	Slump	-	√	√*
	Compressive Strength	√	√	√*
	Resistance to Chloride Penetration	√	√	√*
	Carbonation	√	√	√*
	Modulus of Elasticity	-	√	-
	Permeability to Water	√	-	-
Environmental	Global Warming Potential	√	√	√
	Ozone Depletion Potential	√	-	√
	Acidification Potential	√	-	√
	Eutrophication Potential	√	-	√
	Abiotic Depletion Potential	√	-	√
	Photochemical Ozone Creation Potential	√	-	√
	Cumulative Energy Consumption	-	√	√
	Fresh Water Net Use	-	-	√
	Human Toxicity Potential	√	-	-
	Freshwater Aquatic Ecotoxicity Potential	√	-	-
	Marine Aquatic Ecotoxicity Potential	√	-	-
	Terrestrial Ecotoxicity Potential	√	-	-
	Y – Combined ecological impact	-	-	√
Economic	Base cost of concrete	√	√	-
	Z - Net present value	-	-	√

*the functional indicators in ECO$_2$ are not included in the aggregated sustainability score

4.3. *Step 2: Define alternatives*

The first significant feature of the ECO$_2$ framework is allowing the user to define the project’s functional requirements. The user needs to register the minimum required service life, as well as the value for the minimum required slump and 28 days compressive strength for each scenario. The user also define the type of concrete (plain or reinforced) for functional indicators purpose.

4.4. *Step 3: Define LCA system boundary*

The ECO$_2$ framework was designed to have a Cradle-to-Grave scope. As Figure 4 shows, the study would include the “Production”, “Use” and “End-of-Life” phases. The first assumption in the framework is that the “Use” phase would not include the energy and emissions resulting from the maintenance of concrete while in service. The reason is that according to Hafez et al. (2019), the values for the maintenance are variable largely, which would add randomness to the study [47].

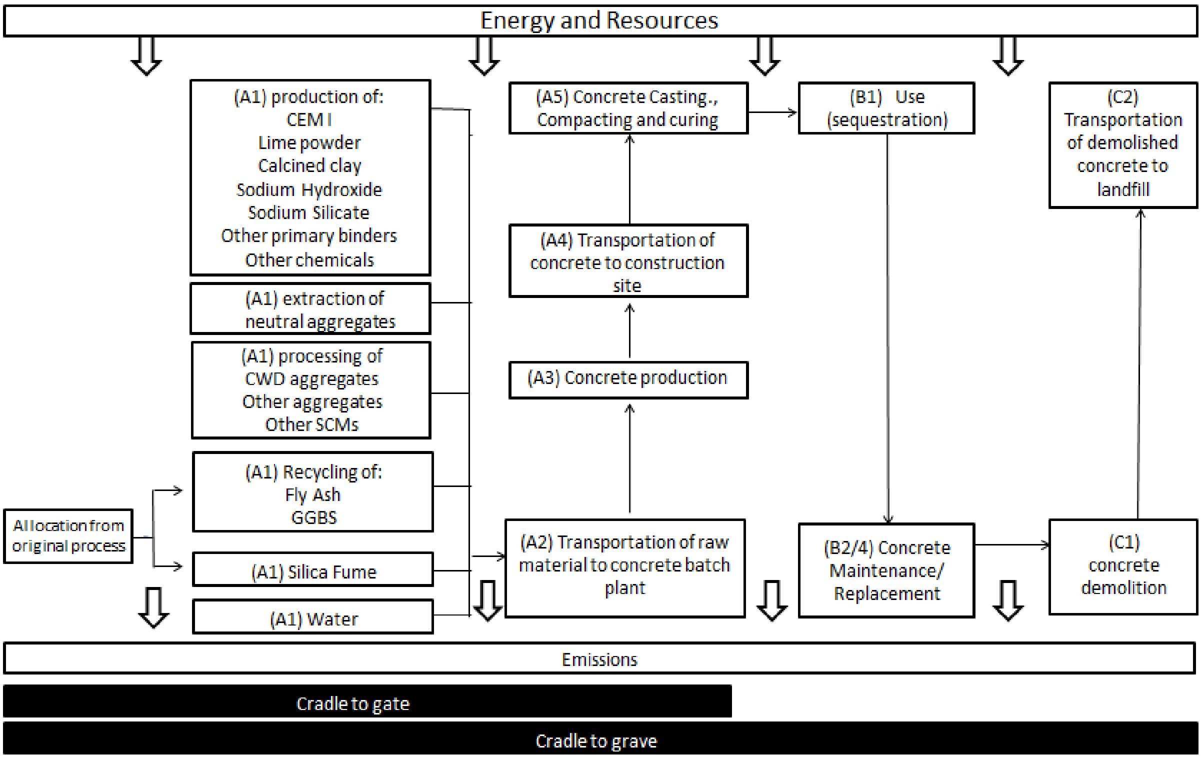

Figure 4: A schematic of the Cradle to Grave system boundary selected for the ECO$_2$ framework

Hence, any concrete alternative is expected to perform in a perfect manner throughout their predicted service life. However, the predicted service of an alternative could potentially fall short of the required service life. Hence, a variable (N) is introduced through the ECO$_2$ framework, which exemplifies the number of times a concrete alternative is replaced, whenever appropriate, to fulfil the required service life. A concrete element that is supposed to sustain itself for the 50 years of service life of a building could suffer from chloride penetration or carbonation and exhibit spalling and steel corrosion after only 25 years, which means that the engineer would then need to prop that roof, demolish the beam and replace it. This means that during the service life of this building, there were (N=2 times) of this concrete volume and this means that when assessing the environmental and economic impact of such volume of concrete (the beam) the user need to be alert that it will be double that of a beam of the same mix that would be able to sustain the whole service life of the building. The second assumption is that the operational energy is not included as a parameter in the assessment. The reason is that structural concrete contributes minimally to the operational energy consumption of a building compared to other building components (less than 3% according to Gursel et al. (2016) [48]).

4.5. *Step 4: Calculate LCA Functional Unit*

Calculating the FU according to the ECO_2 framework is done through two stages. The first is checking if the minimum requirements, which are the workability and strength, are met. Workability is vital for concrete construction and it is largely attributed to the available free water in the concrete mix, which is dependent on the ratio between the volume of the paste and the volume of the aggregates [49]. The most used workability indicator test is the standard cone slump test (BS EN 12350-2). The expected values for the test vary between 0 and 300mm, depending on the height of the cone and are normalized according to the classification listed in EN 206-01 as S1 (0-40 mm), S2 (50-90 mm), S3 (100-150 mm), S4 (160-210 mm) and S5 (220-300 mm). The agreed indicator for concrete strength is the 28 days compressive strength which could is usually tested as per the BS EN 12390-3 standard [50]. Strength is affected by more factors than slump such as curing age, curing conditions, binder composition and water to binder ratio and is dependent on the characteristics of the mortar, coarse aggregates, and the interface between them [51]. First, for every alternative (*i*), the user inputs the values for slump (Yslump) and strength (Ystrength) and if Yslump (*i*) < Yslump (required) or Ystrength (*i*) < Y strength (required), the alternative is rejected.

If an alternative achieves the minimum requirement, the functional unit is defined as per the following equation 1:

$$FU_i = N_i * 1m^3 \tag{1}$$

Where N is the replacement ratio of the concrete alternative, reflecting the number of times it would need to be replaced to fulfil the required service life. If the concrete alternative is plain concrete, or a reinforced concrete used within a dry indoor environment, it is assumed to be durable enough to sustain itself throughout the required service life without need for maintenance or replacement. Hence, N is equals to 1 and FU is equals to 1 m^3 of concrete.

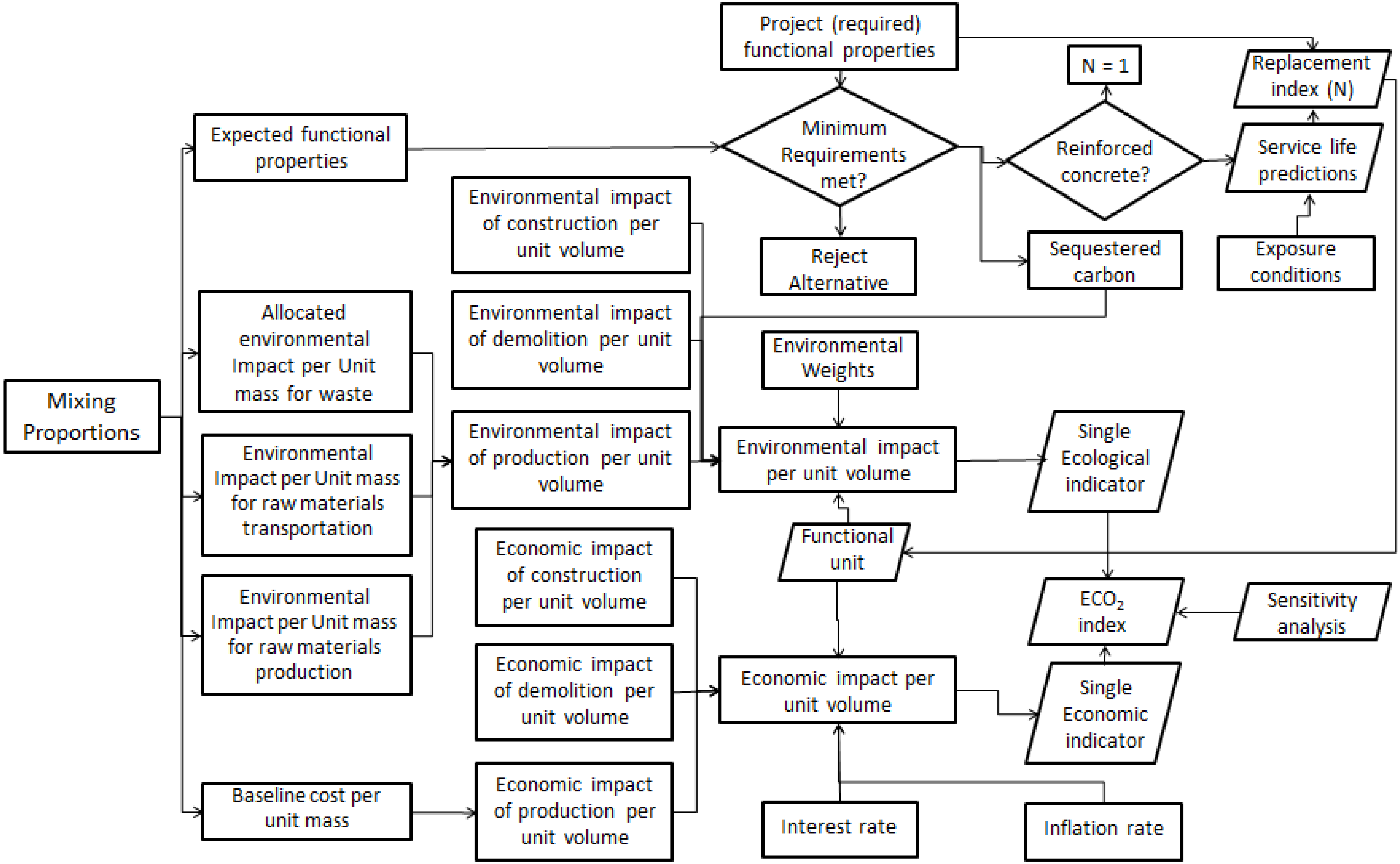

Figure 5: The ECO$_2$ algorithms for calculating the economic and ecological impact of concrete alternatives

For each reinforced concrete alternative, as shown in Figure 5, the user would have registered a value for the required service life (SL_R). Service life of concrete is the time needed till it reaches the ultimate limit of deterioration under specific exposure conditions and upon which either repair or replacement is needed [52]. If the alternative under study is reinforced concrete, corrosion of the steel reinforcement is the main deterioration mechanism, which makes resistance to chloride penetration and resistance to carbonation the main indicators of durability [53].

1. Chloride penetration is the primary mechanism for the corrosion of steel reinforcement in reinforced concrete. For the corrosion to be initiated, which means the compromise of the concrete cover, a parameter identified as the chloride threshold [54]. The chloride threshold potential of a concrete mix is dependent on a set of exposure conditions such as temperature, RH and % of free chlorides as well as intrinsic variables such as the concrete type and w/b ratio [55]. A standard test to measure the resistance of a concrete mix to chloride penetration is called Rapid Chloride Penetration Test (RCPT) according to ASTM C1202–18 [56]. In order to predict the value for the chloride diffusion coefficient D_{nssm}, the following data in table 2 was extracted from the literature for specific concrete types and mixes. Service life predictions against chloride-induced corrosion are defined in standards as the duration that takes the chloride content at the surface of the steel reinforcement to reach the chloride threshold [57]. According to Markeset and Kioumarsi (2017), the most significant parameters in the DuraCrete model of service life prediction against chloride penetration are: D, which is the chloride diffusion coefficient (m^2/s) and C_{cr}, which is the chloride threshold level (%) [58]. The model, which is developed based on Fick's second law of diffusion, predicts the service life SL_{p-cl} as per equations 2 and 3 as the time when C(x,t) is equal to C_{cr}:

$$C(x,t) = C_o * erfc(\frac{x}{2*\sqrt{D_t*t}}) \tag{2}$$

$$D_t = D(\frac{t_o}{t})^{\propto} \tag{3}$$

Where, C_o is the chloride concentration on the concrete surface estimated at 0.5 1%, X is the concrete cover, α is an aging factor and t is the service life expected for the durability against chloride penetration SL_{R-Cl}, in years.

2. Resistance to carbonation. The mechanism by which this carbonation could prove detrimental to the concrete durability by inducing corrosion to the reinforcement is chemical depassivation. The dissolved carbon dioxide from the environment reacts with the calcium hydrate phases of the concrete binder. The process reduces the PH of the carbonated depth of concrete (X_c), which de-passivates the protection layer against corrosion of the steel reinforcement. It is then assumed, in the simple model proposed by Jiang et al. (2000), that the durability of a concrete alternative against carbonation is a measure of the time at which the depth of carbonated concrete (X_c) is equal to that of the concrete cover (X, in cm) [59]. This conservative measure prevents steel from corrosion. A standard method of calculating K_n, the natural carbonation rate of concrete, is to plot the carbonation depth versus the duration of exposure, and then calculate the slope of the best fit curve [60]. The depth of carbonation could be measured from a natural carbonation test or the standard accelerated test LNEC E 391:1993 that is then correlated using equation 4 below. In case primary data is not available, major discrepancies were found in reported carbonation rates of the same concrete type as shown in Table 2. The reason could be that, even if they were the same concrete type, having a mix of lower w/b ratio would have a higher resistance to carbonation [61]. Another reason is the difference between accelerated and natural carbonation testing. Van den Heede et al. (2019) showed that testing high volume FA BCC using an accelerated carbonation setup would overestimate the carbonation rate predicted [60].

$$K_n = K_a\sqrt{\frac{CC_n}{CC_a}} \tag{4}$$

Where K_a is the accelerated carbonation rate, CC_n is the CO_2 % concentration in the environment and CC_a is the that in the carbonation chamber in which the test was done.

Given that the values for the natural carbonation rate (K_n, in mm per square root year), the predicted service life ($SL_{P\text{-}Cr}$, in years) for carbonation could be calculated as per equation 5:

$$SL_{P-Cr} = \left(\frac{X}{K_n}\right)^2 \tag{5}$$

After determining the expected service life for every reinforced concrete alternative according to both mechanisms of deterioration: $SL_{P\text{-}Cr}$ and $SL_{P\text{-}Cl}$ in years, the replacement ratio N would then be calculated as per equation 6.

$$N = \frac{SL_R}{\min(SL_{P-Cr}, SL_{P-Cl})} \tag{6}$$

Table 2: A summary of the values for resistance to carbonation and chloride penetration coefficients from the literature

Reference	Type	OPC % replacement	SCM	Expected carbonation rate k_n (mm/√year)	Expected D_{nssm} (10^{-12} m^2/s)
Silva et al. (2015) [61]	RAC	0	NA	Twice that of OPCC	-
Garcia-Segura et al. (2014) [52]	OPCC	0	NA	4.72	
	BCC	20	FA	4.72	
		35		4.72	
		35	GGBS	5.42	
		50		5.42	
		80		5.42	
Gettu et al. (2018) [29]	OPCC	0	NA	10	-
	BCC	50	FA	24	4.5
		40		17	7.1
		30		17	8.1
		25		17	5.9
		15		14	1.34
		50	GGBS	14	3.2
		30		20	8.9
		15		14	16.4
Cheng et al. (2018) [62]		40		-	18
		35			11
		30			8

4.6. *Step 5: Collect Life Cycle Inventory Data*

The ECO_2 framework includes the production, construction, demolition and the transportation from the source to the batch plant then to the construction site as well as that to the landfill. In addition, the framework allows the user the option to enter site-specific primary data for all processes as well as EPDs for the constituents used in concrete. However, if not available, the framework includes a database of more than 250 data points from published articles, EPDs and extracts from the Ecoinvent database from which the inventory data for the processes understudy can be extracted.

Finally, the ECO_2 framework calculates the impact allocated to FA, GGBS and SF if included in the alternative. This is through either mass allocation as shown in Equation 7 or economic allocation, in which the percentage allocated is based on the relative market value between the final product, which is electricity, as per Equation 8 [41].

$$\text{Mass Allocation} \quad = \frac{(\text{m})_{\text{by-product}}}{(\text{m})_{\text{main product}}+(\text{m})_{\text{by-product}}} \tag{7}$$

$$\text{Economic Allocation} \quad = \frac{(\$.\text{m})_{\text{by-product}}}{(\$.\text{m})_{\text{main product}}+(\$.\text{m})_{\text{by-product}}} \tag{8}$$

Although economic allocation is dependent on the time-dependant market prices of the raw materials, it is the most preferred in the literature. According to Marinkovic et al. (2017), in case the difference between the price of main and secondary process generating the SCM product is more than 25%, economic allocation should be chosen over mass allocation [40]. A study by Chen et al. (2010) supports that the use of economic allocation over mass allocation in case of FA –for example- would usually translate to a lower impact allocated percentage (1% and 12.4% respectively) [41]. Once the percentage allocation is calculated, the allocated impact per unit mass is equal to the same percentage from the impact of the original process, which is either user-input or extracted from the ECO_2 database.

4.7. *Step 6: Calculate the sustainability index*

4.7.1. *Environmental Impact Assessment*

The environmental impact per unit volume is calculated using the aforementioned eight mid-point indicators (Table 1) for each concrete alternative (*i*) understudy as shown in equation 9. For every environmental impact indicator *V*, the impact per unit volume is multiplied by the functional unit.

$$V_i(per\ functional\ unit) = V_i(per\ m^3) * FU_i(calculated\ in\ 3.8) \tag{9}$$

The per unit volume impact indicator *V* is calculated as per equation 10 below. The upstream unit mass impact of each raw material *j* is multiplied by the mass per unit volume proportion of *j* in the mix specified for alternative i and the total impact from the *n* number of raw materials per alternative is added to the per unit volume impact for construction and demolition. For the GWP indicator only, the per unit volume expected sequestered carbon dioxide is deducted from the total.

$$\frac{GWP_i}{m^3} = \sum_{j=1}^{n}\left(\frac{GWP_{j\,upstream}}{kg} * \frac{kg_j}{m^3}\right) + \frac{GWP_i construction}{m^3} - \frac{GWP_i sequestered}{m^3} + \frac{GWP_i\ demolition}{m^3} \quad (10)$$

$$\frac{GWP_{j\,upstream}}{kg} = \frac{GWP_j production}{kg} + \frac{GWP\ transportation}{kg.km} * 1.7 * D_j\ (km) + GWP_j allocated(if\ any) \quad (11)$$

Where D_j is the distance between the source of the raw material (j) and the concrete batch plant (in kilometres)

For every raw material (*j*) included in the concrete mix of this alternative, the value of the upstream impact indicators per unit mass is the addition of that from its production process, transportation and allocation (if applicable) as shown in equation 11.

Carbon sequestration is the term used to describe how much carbon dioxide is absorbed by concrete from the environment. Through the carbonation process concrete can absorb, throughout its whole service life, 13-48% of the carbon dioxide it emitted during the calcination process of the production phase [63]. Since it is only carbon dioxide, the carbon sequestration only affects the GWP environmental indicator. The magnitude of the sequestered carbon is dependent on: exposure conditions and intrinsic variables. The exposure conditions are the exposed surface area of the concrete member, the CO_2 concentration in the environment, the humidity and temperature as well as the exposure time. The intrinsic variables affecting the carbon sequestration potential are the type of binder and the total binder content per unit volume [10]. Hence, the exposure conditions are assumed the same for all alternatives under the same scenario, while the intrinsic variables depend on the mixing proportions and type of cement replacement if any in each alternative. The user can opt to enter primary data for the exposure conditions per scenario or rely on the assumed default values obtained from the literature as shown in table 3.

Table 3: Secondary exposure conditions from the literature in the ECO_2 framework

Concrete Cover (X)	30	mm
Thickness of concrete members	250	mm
Exposed area of concrete	4	m^2/m^3
Average Temperature yearly	23	°C
Average Humidity yearly	60	%
Average Carbon Concentration	0.04	%
Average Surface Chloride Content yearly	0.05	(% by weight of concrete)

There are several models available to predict the amount of carbon sequestered U_{CO_2} of a given concrete alternative after (*t*) days, which is equivalent to the required service life (SL_R). The model used in ECO_2 is as shown in equation 12 based on Yang et al. (2014) [64]:

$$U_{CO_2}(t) = a_{CO_2}(t) * A * X_c * t\ (grams/m^3) \quad (12)$$

Where *A* is the exposed surface area of concrete (in cm^2), X_c is the carbonation depth (in cm) and $a_{CO_2}(t)$ is the amount of absorbable CO_2 in g/cm^3 at time t, which is calculated using equation 13 for each alternative of a total binder content *B* (grams) and Water (grams):

$$a_{CO_2}(t) = 366 * 10^{-6} * B * \frac{t}{2+t} * \frac{W/_B}{W/_B+0.194} \tag{13}$$

4.7.2. Economic Impact Assessment

The economic impact per unit mass of the production and transportation of each raw material are summed together as per equation 14 to produce the baseline cost (C_b) of each alternative (i).

$$C_b = \sum_{j=1}^{n}\left(\frac{(C_p+(C_t*D_j))}{kg} * \frac{kg_j}{m^3}\right) \tag{14}$$

The unknowns in equation 14, C_p and C_t, are the market price per unit mass and the transportation cost per unit mass and unit distance of each raw material respectively. D_j is the transportation distance, which equals the geographic distance between the source of the raw material and the concrete batch plant. The reason the geographical distance is not multiplied by 1.7 as in the environmental impact assessment is that the return trip is accounted for in the price assumed for the service. Kg_j/m^3 describes the value of the mixing proportion for this raw material *j* in the alternative *i.* Similar to the process of environmental impact assessment, the value for *C,* the economic impact per unit volume of alternative (*i*) is calculated using equation 15. It should be noted that C_c and C_d stands for the cost per unit volume of the construction and demolition processes respectively.

$$C_i = C_b + C_c + C_d \tag{15}$$

For both frameworks reviewed, the economic impact indicator is simply the baseline cost. However, this is not representative of the whole service life cost of the concrete since this baseline cost is repaid every time the reinforced concrete alternative is to be replaced in the case the predicted service life falls short of the required one. Hence, the ECO_2 framework presents an economic index, *Z*, representing the net present value of the expected cash flow of the concrete alternative *i*. Hence, Z is the total of all accumulated costs of replacing each alternative N times, while taking into consideration the time value of money. According to Panesar et al. (2013), in order to calculate *Z*, the real interest rate F_r needs to be derived by setting the interest rate F_i to negate an inflation rate of F_f as per equations 16 and 17 [46].

$$F_r = \frac{1+F_i}{1+F_f} - 1 \qquad (16)$$

$$Zi = \frac{C_i}{(1+F_r)^t} \qquad (17)$$

4.8. *Impact normalization and aggregation*

The final component of a typical MCDA prior to judging the set of alternatives studied under a certain scenario is normalization [65]. Normalization is the step at which the score of each indicator is scaled to a benchmark value [3]. As explained in the introduction, the ECO$_2$ tool is not intended for LCA experts. Hence, in order for the user to interpret the values of the environmental and economic indicators, its needs to be normalized as shown in equation 18.

$$V_i^{'} = \frac{max\,(V_i) - V_i}{max\,(V_i) - min\,(V_i)} \qquad (18)$$

A normalized values for each indicator would be a value ranging from 0 to 1. After that, the normalized value of the single score ecological impact (*Y*) for each alternative (*i*) is calculated as per equation 19 where *Wv* is the variable representing the weight given for each mid-point environmental indicator *V* and subsequently its normalized value *V'*. These weights are either user-input according to the user's preference or would be assume equal as in table 4:

$$Y_i = \sum V_i^{'} * W_v \qquad (19)$$

Table 4 An extract of the sustainability weights from the secondary database of the ECO$_2$ tool

Weight of sustainability Indicators (default)	GWP	ODP	AP	EP	ADPE	POCP	CED	FW
	13%	13%	13%	13%	13%	13%	13%	13%
	Ecological W_{E1}	Economic W_{E2}						
	50%	50%						

Finally, ECO$_2$, which is the single sustainability assessment index that combines is calculated. According to the equation 20, ECO$_2$ is calculated for each alternative (*i*) by combining the single ecological (Y_i) and economic (Z_i) indicators together based on their weights W_{E1} and W_{E2}.

$$ECO_{2_i} = Y_i * W_{E1} + Z_i * W_{E2} \qquad (20)$$

5. Case study

After explaining the distinctive features of the ECO_2 framework, it is necessary to observe how different the new logic is compared to both existing frameworks, MARS-SC and CONCRE*Top*. In order to clarify the differences, the comparison is done between 3 concrete mixes under 2 different scenarios.

The hypothetical case study assumes a construction project requires 2 concrete mixes: a plain concrete one and another reinforced. The minimum required slump, 28 days compressive strength and service life are 200mm, 30 MPa and 50 years respectively. The three mixes under study are shown in table 5. The mixing proportions and resulting functional properties are assumed for demonstration purposes based on a 50mm concrete cover.

Table 5: The mixing proportions of the three alternatives under study

	Mix 1	Mix 2	Mix 3		
CEM-1	250	125	125		Mixing Proportions (g/m^3)
FA	0	125	0		
GGBS	0	0	125		
Coarse Agg	1050	1050	1050		
Fine Agg	950	950	950		
Water	165	165	165		
Superplasticizer	2.5	2.5	2.5		
Slump	200	280	220	mm	Fresh and mechanical properties prediction
28 days Compressive strength	40	35	30	Mpa	
Carbonation	100	20	40	Years	Service life prediction
Chloride penetration	100	150	200	Years	
Basic Unit cost	90	80	70		\$/m^3

As an approximation, the environmental indicators selected for the comparison between the frameworks are the global warming potential (GWP) and cumulative energy demand (CED). The inventory data necessary for the calculation of the impact for the LCA of the 3 mixes could be summarized as shown in table 6. The average values for each component of the LCI were obtained from the ECO_2 database. The transportation distances of concrete from the batch plant to site and from the site to landfill are assumed as 50 and 100km respectively. The economic impact allocation for FA and GGBS are assumed as 2 and 1% from electricity and steel production respectively. Finally, the energy required for the construction and demolition processes of concrete is assumed as 100 kWh.

Table 6: Inventory data for the hypothetical case study

Component	Unit	GWP kg eCO$_2$/unit	CED MJ/unit	Transportation Distance km
CEM-I	kg	0.896	4.193	152
FA (no allocation)	kg	0.006	0.438	446
GGBS (no allocation)	kg	0.040	0.685	564
Coarse aggregates	kg	0.010	0.072	184
Fine aggregates	kg	0.007	0.058	184
Superplasticizer	kg	0.908	19.822	539
Transportation by truck	t.km	0.290	3.148	
Energy grid use	kWh	0.037	0.830	
Electricity from coal	kWh	0.319	0.001	
Steel production	kg	1.473	20.187	

The main difference in the logic of the ECO$_2$ framework than MARS-SC and CONCRE*Top* is the functional assessment of concrete. According to both reviewed frameworks, the functional impact of an alternative is calculated based on the local comparison of the alternatives in terms of measured performance regardless of the project specifications. Hence, the functional impact of alternatives 1, 2 and 3 would be calculated as follows:

Table 7: Functional Impact Calculations for the three reviewed frameworks

	Mix 1	Mix 2	Mix 3	
Slump	200	280	220	mm
28 days c. Strength	40	35	30	MPa
Carbonation	100	20	40	Years
Chloride penetration	100	150	200	Years
Slump	1.0	0.0	0.8	normalized
28 days c. Strength	0.0	0.5	1.0	
Carbonation	0.0	1.0	0.8	
Chloride penetration	1.0	0.5	0.0	
Functional performance	0.5	0.5	0.625	MARS-SC and CONCRE*Top*
Required service life	50	50	50	ECO$_2$
minimum service life	100	20	40	
FU (PC scenario)	1	1	1	
FU (RC scenario)	1	2.5	1.25	

On the other hand, ECO$_2$ consider the functional performance compared to the project requirements by integrating it into the functional unit calculations for the LCA. As explained in section 3.2, the three mixes pass the minimum requirements since the slump and strength are higher than the project requirement. Hence, the functional unit of each alternative is calculated as shown in table 7. Furthermore, the environmental impact assessment is calculated per unit volume of concrete by multiplying the inventory data of each mix constituent by its mixing proportion in each alternative. The three sustainability assessment being compared, MARS-SC, CONCRE*Top* and ECO_2 all have a similar process for the production impact per unit volume as shown in table 8.

Table 8: Environmental Impact of concrete production per unit volume using the three frameworks

			Production impact
Alternative 1	GWP	kg eCO_2/m^3	362
	CED	MJ/m^3	2510
Alternative 2	GWP	kg eCO_2/m^3	261
	CED	MJ/m^3	2157
Alternative 3	GWP	kg eCO_2/m^3	269
	CED	MJ/m^3	2234

However, due to the fact that it considers a whole life cycle scope, the ECO_2 adds the impact of allocation, transportation, sequestration and construction and demolition. Hence, the impact assessment of each alternative according to the ECO_2 is always higher in absolute values with 10-20% than that calculated using MARS-SC and CONCRE*Top* as seen in table 9 and Figure 6.

Table 9: Environmental impact of whole life cycle of concrete per functional unit as per ECO_2 framework

		Unit/ FU	Impact allocation	Transportation Impact	Carbon Sequestration	C&D Impact	Scenario 1 (PC)	Scenario 2 (RC)
Alt 1	GWP	kg eCO_2	0	28.9	-16.24	70.54	445	445
	CED	MJ	0	314.7	0	485.06	3309	3309
Alt 2	GWP	kg eCO_2	0.827	28.9	-18.14	70.54	343	514
	CED	MJ	0.002	314.7	0	485.06	2956	4435
Alt 3	GWP	kg eCO_2	2.671	28.9	-14.71	70.54	356	891
	CED	MJ	36.592	314.7	0	485.06	3070	7676

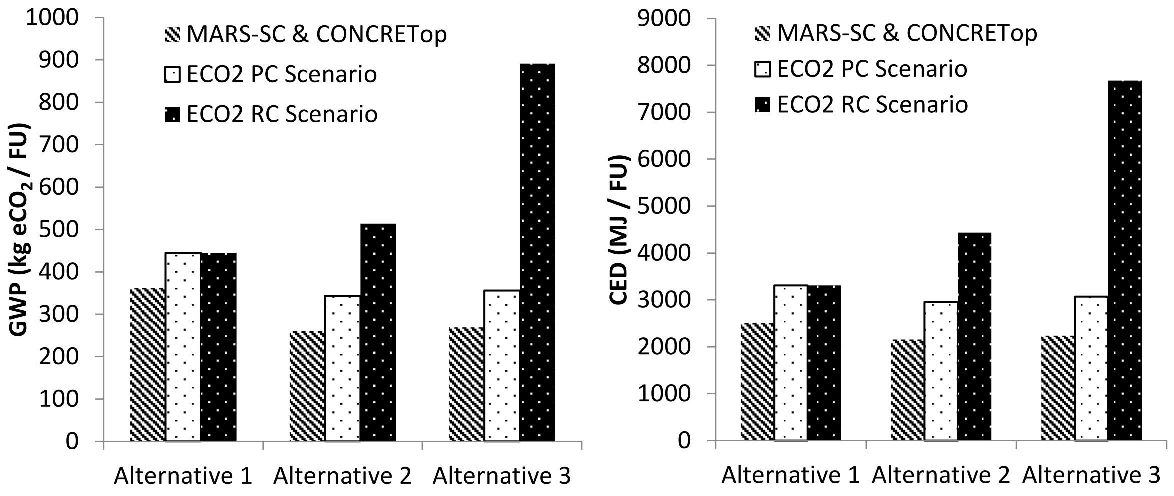

Figure 6: Comparison between the values of environmental impact indicators GWP (left) and CED (right) of the reviewed frameworks and ECO$_2$

Regarding the third pillar; the economic impact assessment, the reviewed frameworks simply compare the basic cost per unit volume of the concrete mixes as seen in table 5. This means that since alternatives 1, 2 and 3 costs 90, 80 and 70 $\$/m^3$ respectively, the score would be 0, 0.5 and 1. On the other hand, ECO$_2$ builds on a more reliable economic measure, which is the net present value of each alternative. For plain concrete, since the alternatives are expected to fulfil their service life requirement, the net present value is similar to the total cost, but the costs of transportation, construction and demolition are added as shown in table 10. Moreover, assuming an interest rate 0.5% and an inflation rate of 2%, for the reinforced concrete scenario, the NPV of alternatives 1, 2 and 3 would be equal to 105, 220 and 130 $\$/m^3$.

Table 10: The economic impact assessment as per the MARS-SC and CONCRETop frameworks and ECO$_2$

production cost	90	80	70	$\$/m^3$
Total cost	90	80	70	MARS-SC and CONCRE*Top*
Economic impact score	0	0.5	1	
transportation cost	5	5	5	$\$/m^3$
construction and demolition cost	10	10	10	
Net present value (PC scenario)	105	95	85	
Net present value (RC scenario)	105	220	130	
Economic impact score (PC scenario)	0	0.5	1	ECO$_2$
Economic impact score (RC scenario)	1	0	0.8	

Finally, the sustainability assessment index is generated by calculating a weighted average between all considered pillars. As seen in Table 11, although the values obtained from MARS-SC and CONCRE*Top* are different than that obtained from ECO$_2$, the judgment/ranking of the alternatives is the same. In the PC scenario, mix 3 with the GGBS is the best, followed by the FA mix and finally the OPC mix. This could be attributed to the fact that the SCMs have lower environmental impact and are cheaper than OPC. This would have also been the same if the reinforced concrete scenario was assumed to be within a dry indoor environment where no corrosion is expected. However, in case of RC concrete (scenario 2), due to the higher service life expected for the OPC mix, mix 1 ranks the most sustainable, followed by the GGBS alternative and finally the FA one.

Table 11: Single scope sustainability assessment of the three alternatives using MARS-SC, CONCRE*Top* and ECO$_2$ frameworks

		Functional performance	Environmental performance	Economic performance	Sustainability Index
Mix 1	MARS-SC and CONCRE*Top*	0.5	0	0	0.17
	ECO$_2$ (PC scenario)	-	1	0	0.50
	ECO$_2$ (RC scenario)	-	0.81	1	0.91
Mix 2	MARS-SC and CONCRE*Top*	0.5	0	0.5	0.33
	ECO$_2$ (PC scenario)	-	1	0.5	0.75
	ECO$_2$ (RC scenario)	-	0.72	0	0.36
Mix 3	MARS-SC and CONCRE*Top*	0.625	1	1	0.88
	ECO$_2$ (PC scenario)	-	0.75	1	0.88
	ECO$_2$ (RC scenario)	-	0	0.8	0.40

6. Conclusions

In this paper, a new MCDA framework "ECO$_2$" was introduced. This would allow engineers and concrete researchers to assess, relatively, the sustainability of several concrete mixes. The key improvements in the methodology followed in the ECO$_2$ framework build on the gaps identified in existing frameworks and could be summarized as listed below:

i. An LCA functional unit representative of performance-based specifications
ii. Prioritize the use of primary data as inventory for LCA
iii. Including the whole life cycle boundary system of concrete
    a. Deducting the sequestered carbon dioxide
    b. Include the environmental impact allocation for industrial by-products
    c. Account for time value of money in economic impact
iv. The framework is dynamic and includes a learning dimension

In order to validate the framework, a case study was prepared comparing three commercially available concrete alternatives: OPC, 50% FA and 50% GGBS. The case study showed that, assuming the same inventory data for the three frameworks under comparison, the MARS-SC, the CONCRE*Top* and ECO$_2$, due to the inclusion of the whole life cycle of concrete, the environmental and economic impact indicators values are 20-30% higher in case of ECO$_2$ compared to the other two. In terms of the relative sustainability assessment, the ranking of the three alternatives was highly dependent on the assumed scenario. In case of plain concrete, all three frameworks ranked the alternatives in terms this order best to worst: GGBS, FA and OPC. It clearly shows the enhanced environmental and economic performance of SCM based alternatives. However, based on the RC scenario, the ranking changed to OPC, GGBS and FA being the worst. This could be due to the fact that the ECO$_2$ framework compares the functional performance of the alternatives to the project requirements which in this case was in favour of the OPC based concrete. However, the results for the functional performance of the reinforced concrete scenario would have changed given a different concrete cover or exposure conditions such as moisture content, CO$_2$ concentration or surface chloride concentration. It should also be noted that the concrete mixes were chosen to demonstrate the ECO$_2$ framework and that altering the w/c ratio might also change the ranking. It is important that the concrete composition is chosen based on exposure conditions.

Finally, the next step for the ECO$_2$ is to develop web-based software that could be accessed by concrete engineers and researchers to allow for the application of the framework on a wide scale and to report gaps and problems as well as enriching the inventory database.

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